

COSTING AT THE SPEED OF LIGHT: HOW YOUR CONCURRENT ENGINEERING DESIGN TEAM CAN BOOTSTRAP YOUR ORGANIZATION'S PROGRAMMATIC CAPABILITIES

Jairus Hihn⁽¹⁾, Tom Youmans⁽¹⁾, Michael Saing⁽¹⁾, Matthew Ramirez⁽¹⁾

*(1) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Ave, Pasadena, California,
United States of America, jhihn@jpl.nasa.gov*

ABSTRACT

What do you do when it is necessary to generate reasonable cost estimates at the earliest Concept Maturity Levels and you have never flown any similar missions before? This paper describes the current and future Team X cost processes and methods, how they are being used to expand our data frontiers and cost modelling capabilities, and how this enables the ability to estimate early and estimate often.

1. INTRODUCTION

Developing space missions, especially space science missions, presents many programmatic challenges. Foremost is that there are not that many historical missions to base an estimate on. The estimation problem is further exacerbated because science missions need to constantly be returning new science results which, especially for planetary missions, requires the use of new configurations and technologies. The fundamental problem is that there are so few historical data points and they do not span the design-cost parameter space required to estimate future missions. For example, this problem would arise if all of one's past missions are planetary orbiters and now one needs to design and cost a rover or a submarine to study a lake on Titan. Clearly, estimating the mission cost and schedule during the lower Concept Maturity Levels will be difficult if you have never flown any similar missions before. So, what do you do to produce realistic ball park estimates when you go 'where no one has gone before'?

For organizations with early concept design teams such as JPL's Team X that include cost estimates as one of their products, you can 'bootstrap' your available parameter reference set by combining technical and cost parameters from historical actuals, high quality design studies, and winnable proposals into a single database. The data from concepts that have not flown still have informational value, but with greater uncertainty (noise) than historical data. They provide insight into technical and cost parameter combinations associated with mission designs that are in the 'ballpark'. This data can be used to improve our ability to estimate cost and technical parameters for a wider range of missions or possibly with a lower level of granularity by providing additional source of analogies as well as data that can be used to develop and calibrate a wide range of cost models that are used across the CML1 to CML 4 range. The CML 1 and

CML 2 models are few and use a small number of inputs with wide confidence intervals while the CML 4 models are many and have a larger number of inputs with estimates that have greater fidelity and tighter confidence intervals.

2. CONCEPT MATURITY LEVELS AND CONCURRENT ENGINEERING TEAMS

Concurrent engineering was first applied to space science mission concepts at the Jet Propulsion Laboratory (JPL) in 1995 as a response to tightening national budgets and the resulting challenge to the Agency to create new methods to do NASA's work "faster, better, cheaper". Today, at many NASA Centers and other aerospace organizations, it is a standard concept design approach fully integrated into the organization's formulation support processes. Team X at the Jet Propulsion Laboratory [1][2], the Integrated Design Center at the Goddard Space Flight Center [3], COMPASS at the Glenn Research Center [4], the Advanced Concepts Office at the Marshall Space Flight Center [5], the Concept Design Center team at the Aerospace Corporation, and the Concurrent Design Facility at the European Space Research and Technology Center (ESTEC) [6] are only a few examples of concurrent engineering teams currently in operation.

Concurrent Engineering (CE) is a systematic approach of diverse specialists collaborating simultaneously in a shared environment, real or virtual, to yield an integrated design. Concurrent design sessions involve a team of mission designers—generally including mechanical, telecom, command and data handling, propulsion, power, guidance and navigation, integration and testing, cost, and other relevant subject matter experts. The team of engineers and designers work together to communicate system level requirements between the subsystems verbally and through an integrated modeling environment [7][8].

Concurrent design sessions can start with various initial inputs anywhere from a rough mission concept including science objectives and destination to more detailed specifications about the instrument suite, including a set of mass, power, thermal, pointing and data volume requirements. The final product in most cases is a closed design for the mission and spacecraft that supports the instrument suite within cost and mass

constraints [9].

Concept Maturity Levels (CMLs) were developed at JPL to provide an ontology to clearly understand and communicate the different stages of a mission design [11,12]. See Table 1 and Figure 1 for a high-level overview of CML's.

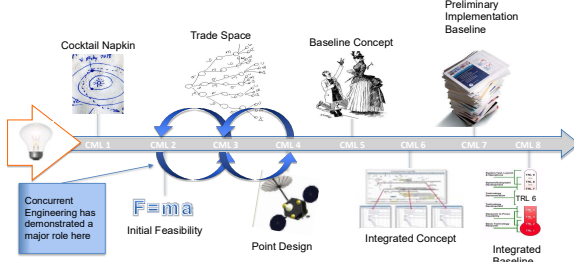


Figure 1: Concept Maturity Level Overview

Table 1: Concept Maturity Levels 1-4 Descriptions [12]

CML	Description
CML 1 Cocktail Napkin	The science questions have been well articulated, the type of science observations needed for addressing these questions have been proposed, and a rudimentary sketch of the mission concept and high-level objectives have been created
CML 2 Initial Feasibility	A “notional” design point has been selected, objectives have been specified, key performance parameters quantified and basic calculations have been performed. These calculations, to first-order, determine the viability of the concept
CML 3 Trade Space	Exploration has been done around the notional objectives and architectural trades between the spacecraft, ground system and mission to explore impacts on performance, cost and risk
CML 4 Point Design	A specific design and cost have been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Subsystems trades have been performed
CML 5 Concept Baseline	Implementation approach has been defined including partners, contracting mode, integration and test approach, cost and schedule. This maturity level represents the level needed to write a NASA Step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects)

This became important as JPL's concurrent engineering teams began to evolve from Team X (CML4 Team) into earlier CML teams that explored notional designs such as the A-Team (CML1-2) because the lower level CML teams often need to pass on their outputs to other teams in order to conduct higher level trade studies (CML3) or point designs (CML4). Also, it is important to understand what different CML level teams can and cannot do [13].

The focus in this paper are the CML1 to CML4 cost tools and processes. CML1 to CML4 is when the mission design evolves from a very general concept into the initial cut at a feasible high-level point design as produced by a concurrent engineering team such as JPL's Team X (See Fig. 1). As design matures, uncertainty reduces across all technical and cost parameters. One of the things we need to measure better is by how much the uncertainty reduces. Table 1 provides a more detailed description of the lower CML levels. For a complete discussion of CML see [11, 12].

3. FOUNDRY DESIGN-COST PROCESS

JPL's CML 4 team, Team X, has a well-defined and well-established process from the initial interaction with a customer through the closeout of a study and the archiving of system's technical and cost parameters. Team X has estimated cost in real time as part the design session since it began in 1995. The design process is currently undergoing a major transformation to enable Team X and all of the JPL concurrent engineering teams to implement a model-based engineering architecture that is more flexible in incorporating new models. The flexibility will allow use of the infrastructure outside of the teams, systematically pass parameters between the teams, and capture every parameter value so it can be quickly reinstated or can be used for later reference and analysis.

Fig. 2 provides an overview of the Team X design process as it will work in 2019. This new process at this level of abstraction is very similar to the original process. Many of the differences are in ease of use and portability as described above. The primary high level additions are:

- MCDB or Mission and Cost Database which archives WBS level 3 technical and cost parameters from design studies, proposals and historical missions.
- Hardware catalogue which contains database of standard parts with their associated parameters
- Early warning cost estimates to catch non-closure problems earlier in the process. Even as early as the initial planning activity.

The current basic flow within the team is to: identify all constraints, identify power modes, set the top-level schedule milestones and phase lengths, complete subsystem level design while monitoring mass roll ups and power supply and demand for each mode, estimate cost using the Institutional Cost Models (ICMs), iterate if constraints are violated until the design closes. On some occasions, a study does not close. This occurs most often due to optimistic customer plans and assumptions or when evaluating mission with many new elements.

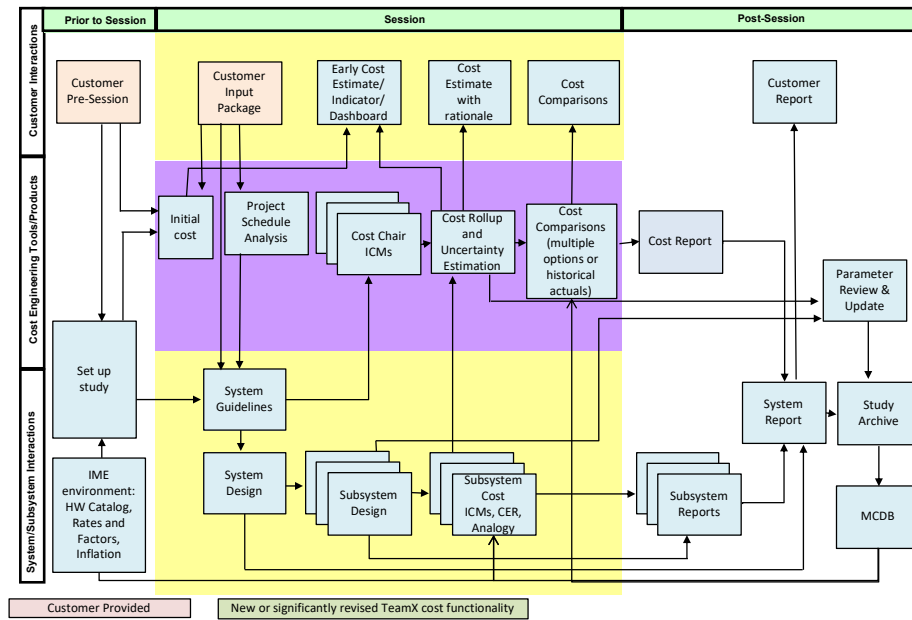


Figure 2: Team X Design Process

A key element of the ICMs and the engineering design models is that they all are linked through a database that passes all of the required inputs and outputs so that every chair is working with a consistent set of information, as is notionally displayed in Fig. 3. This system not only keeps everyone on the same page, but it also is what makes it possible to reuse the data to provide analogies and support model development.

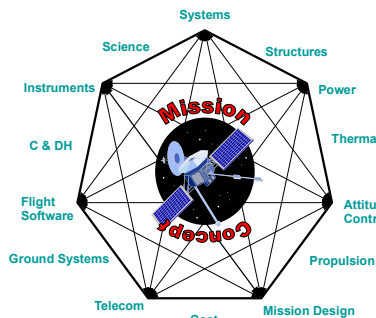


Figure 3: All Team X Models are Integrated Passing Data in Real Time

The ICMs are mostly what can be called grass roots cost simulators. The only exceptions are the Instrument (NICM) and Flight Software Cost models, which are parametric. Fig. 4 shows an example of the Project Management ICM which is one of the simpler cost models in Team X. As can be seen, it is basically a workforce look up table.

A very important part of the cost process on Team X goes on outside of the study process shown in Fig. 2. The ICMs in Team X are owned by the sections that implement that part of the mission or system. This means that the estimates are considered to be a valid

first order estimate that the sections must stand behind. All ICMs are (re)validated on a periodic basis to evaluate the estimation error. If any changes are made to the ICM, then several activities are initiated. The new model must be validated against actuals and high quality proposals. The estimates are required to be within +/- 30% of the actuals. Changes in the estimates between versions must be documented. In addition to the rigorous verification testing, any model update must go through an extensive integration test before it is allowed to be used during a live session. Finally, a Change Control Board (Cost CCB) is convened with members representing all of the engineering and science organizations. At the CCB, all of the results are presented and evaluated. It is for these reasons that any cost estimates from Team X studies that are identified as containing sufficient valid information by the Cost Chair, Systems Chair and the Facilitator can be exported into the MCDB for use in developing future estimates.

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4. IT TAKES MORE THAN ONE MODEL

As one moves through the CML levels, knowledge of the system requirements and design becomes more accurate and detailed. The result is that the number of inputs in which one can have confidence grows, and the estimation uncertainty of the cost, mass and power greatly decreases. For example, at CML 1, errors of +/- 100% are not uncommon, while at CML 4 and 5 we often plan for +/- 30%. It is considered a best practice in the cost engineering field that the right method be used given the available information. Fig. 5 shows how what are recognized as the best estimation methods evolve, as the CML levels increase, from high-level models with few inputs to detailed effort-loaded schedules. Using multiple estimation methods is also highly recommended in the early stages due to the large estimation uncertainty. This can be thought of as estimation triangulation. The flow is from estimation based on high-level analogies, to rules of thumb, then to regression-based model and cost estimating relationships (CERs). As discussed in the previous section, Team X uses bottom up simulation models, but these are models with a small number of inputs based on standard labor distributions for different types of missions, not detailed bottom up estimates. Fig. 6 shows the complete set of JPL cost models/tools used throughout formulation. As can be seen, we use multiple models at all stages and continue to develop these tools and models as more data becomes available.

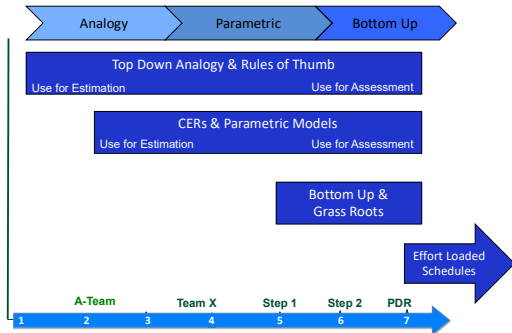


Figure 5: Estimation Methods Across the CML Levels

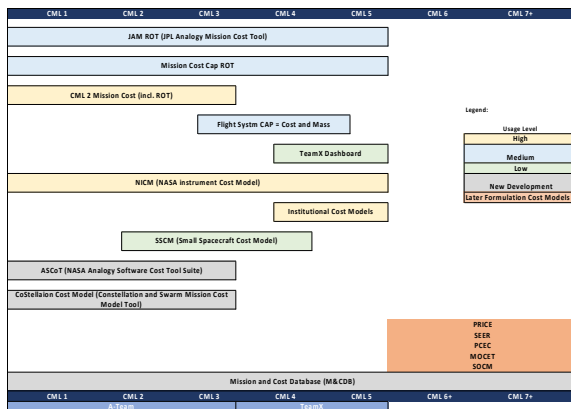


Figure 6: JPL Cost Models by CML Level

Figs. 7, 8, and 9 show examples of some of the most frequently used system cost models. Rules of thumb models are useful at every CML level. For example, the CML 2 model shown in Fig. 9 requires an estimate of the payload cost, which can be derived from the NASA Instrument Cost Model (NICM), then uses rules of thumb to estimate every other WBS element. The JPL Analogy Model or JAM is the CML1 cost model. It allows one to search a database using standard descriptors such as destination and mission type. Based on the records returned, scatter plots and cost distributions are produced. JAM uses data from a combination of actuals, proposals and studies. The data is color-coded by each of these three categories and one can filter the data based on the source of the data. This allows various forms of analysis and comparisons [14].

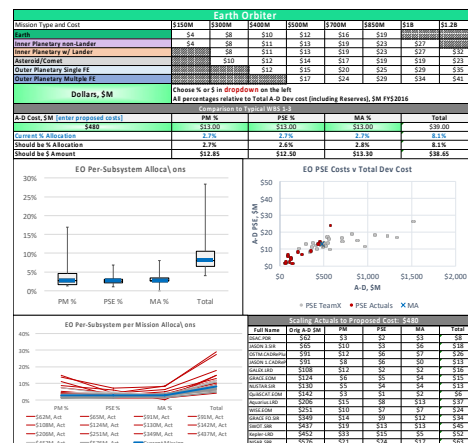


Figure 7: Example of CML 4 to 7 Rule of Thumb Tool

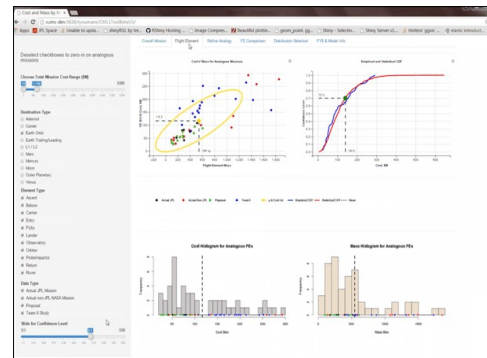


Figure 8: CML 1 Analogy Cost Tool

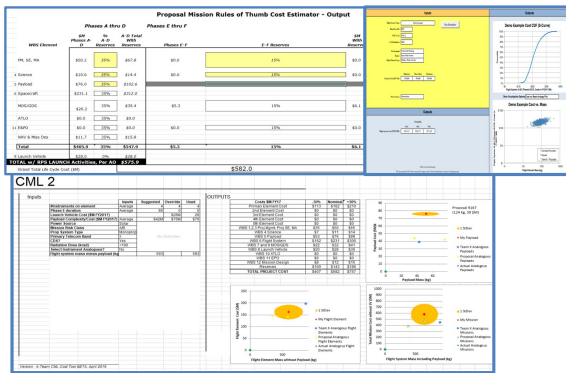


Figure 9: CML 2 Cost Tool

Most of these models could be built without combining data from actuals, design studies and proposals. The design studies provide data on novel ‘missions’ that have not flown yet. and they always have a comprehensive parameter set at multiple levels is consistent and exactly follows the standard WBS definitions. The model calibrations and predictions are carefully analysed so that differences between the actuals and other data are understood and documented. When generating scatter plots, the different data sources are always color-coded.

5. MCDB: THE MISSION AND COST DATABASE

Many organizations struggle with establishing and maintaining a gold reference for their cost and technical data. This shows up especially at proposal time when everyone is quoting data from different sources as proposal teams attempt to sell a proposal. The data being referenced represents snapshots of the data or based on different definitions of what is included. The analogous costs quoted are almost always favourable to the proposal.

Building a ‘gold standard’ database has been attempted before at JPL and those attempts have all failed. There are two primary oversights that cause failure. The first and most important is to have a small team that enforces data quality verification and normalization of the data in a consistent manner. The second is that there needs to be sufficient buy-in from all stakeholders.

The MCDB is an online database and is being designed so that various data views can be quickly accessed in the various concurrent engineering teams. Standard data views include scatter plots, user defined data summaries, and simple lists of analogous missions and studies. Over 500 cost and technical parameters at the system and subsystem levels have been identified. The MCDB also includes extensive descriptive information for context and identification of the original data sources.

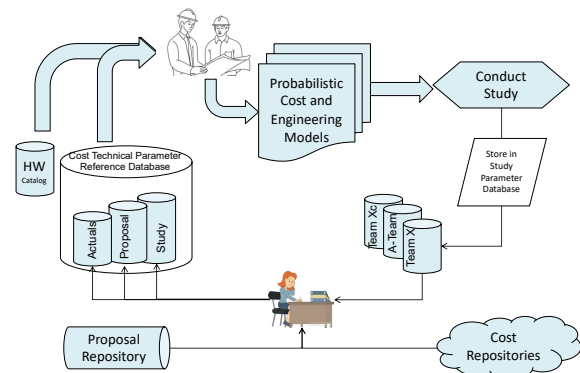


Figure 10: Mission and Cost Database Process

More detailed data analysis can be conducted outside of study sessions by exporting selected data to various data analysis tools such as R and Tableau and to our homegrown tools. Another key feature of the new infrastructure is the capability to export complete parameter sets from high quality Team X studies that can be used to supplement the relatively small set of data from historical missions. This enables us to fill in many gaps in the historical record and, as mentioned previously, it captures expected changes in technology and development processes. While the historical record is important and anchors the estimate, it is only part of the story.

6. NEXT STEPS AND CONCLUSIONS

The primary next steps are to complete development of the new concurrent engineering infrastructure and the Mission & Cost Database (MCDB). These two items enable virtually everything else that provides us the ability to estimate early and estimate often. One big improvement arising from the creation of an integrated MCDB is that it will allow us to constantly validate ICM performance as new actuals come in.

Currently, there is major focus on creating much more sophisticated rules of thumb models that combine cost, mass, power and number of instruments along with other key parameters. For example, JPL has flown enough Discovery Class Planetary Missions that we can document that \$500M can only produce missions within certain mass ranges, data rates and payload sizes. The new rules of thumb will make it possible to, quickly and in the first days of a proposal, flag proposed missions that will have great difficulty getting under the budget cap no matter how much they manipulate the details of their mission design.

The bottom line, however, is that for any organization with a CML 4 concurrent engineering team can be used greatly enhance an organizations cost estimation capabilities as long as estimating cost is part of what it means to have produced a closed design.

7. REFERENCES

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